

Study the QCD Phase Structure

Recent Results from ALICE at LHC & STAR at RHIC

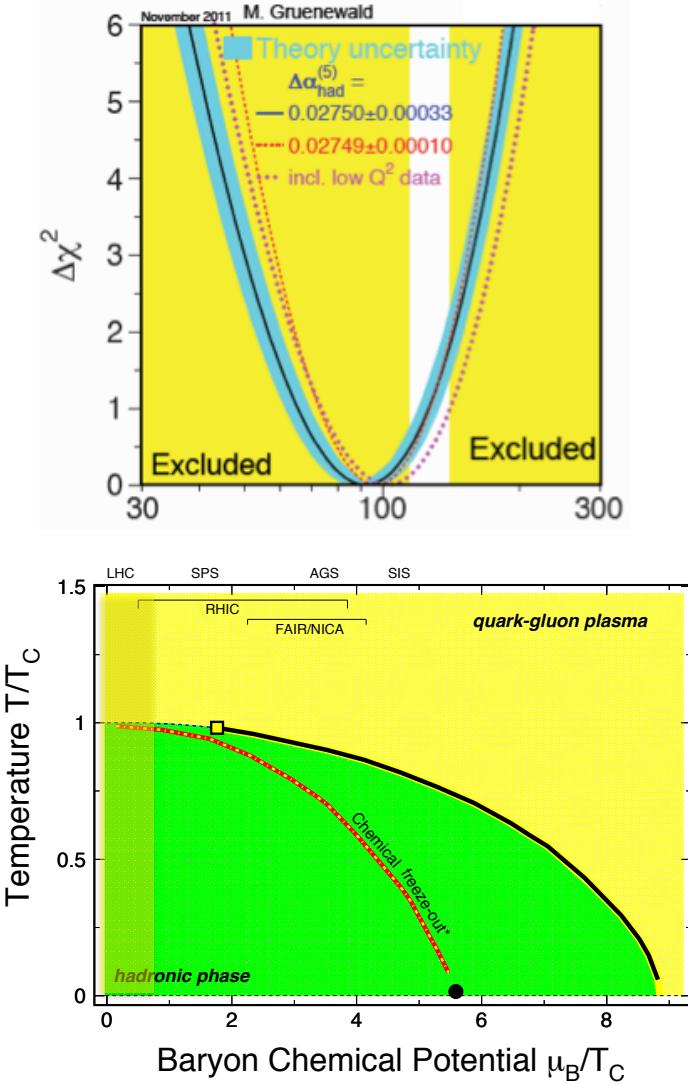
Nu Xu (许怒)

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⁽²⁾ Nuclear Science Division, Lawrence Berkeley National Laboratory, USA



Many Thanks to the Organizers!



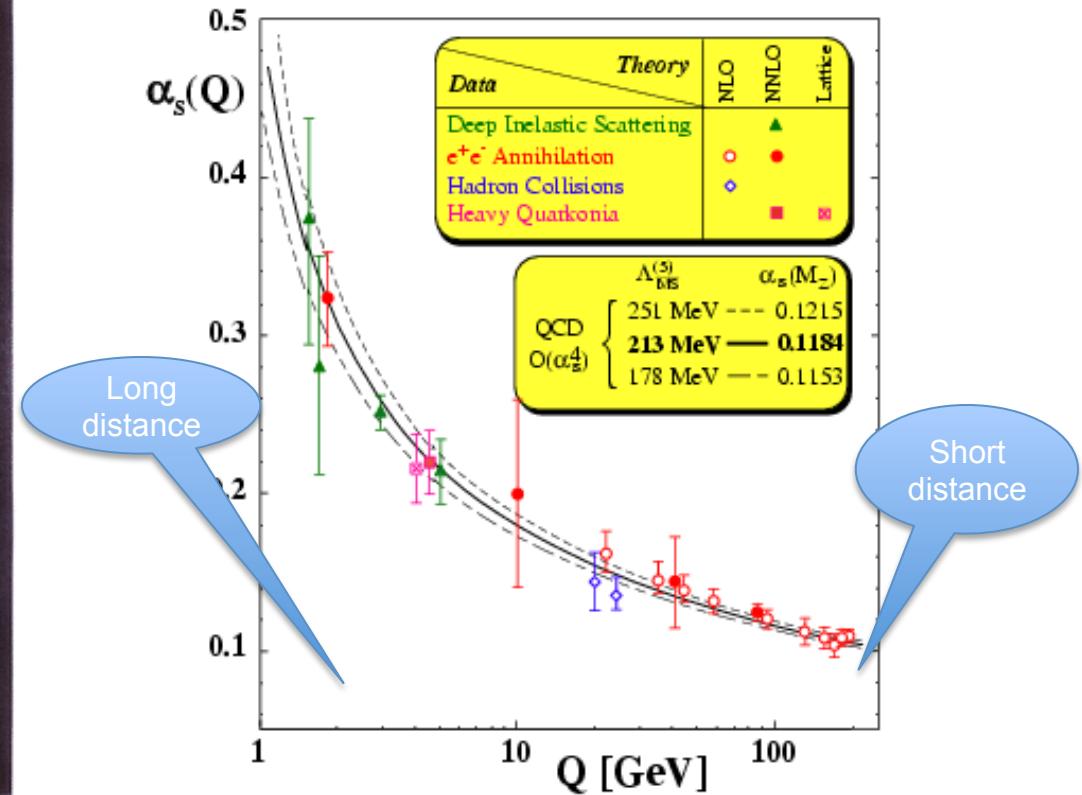
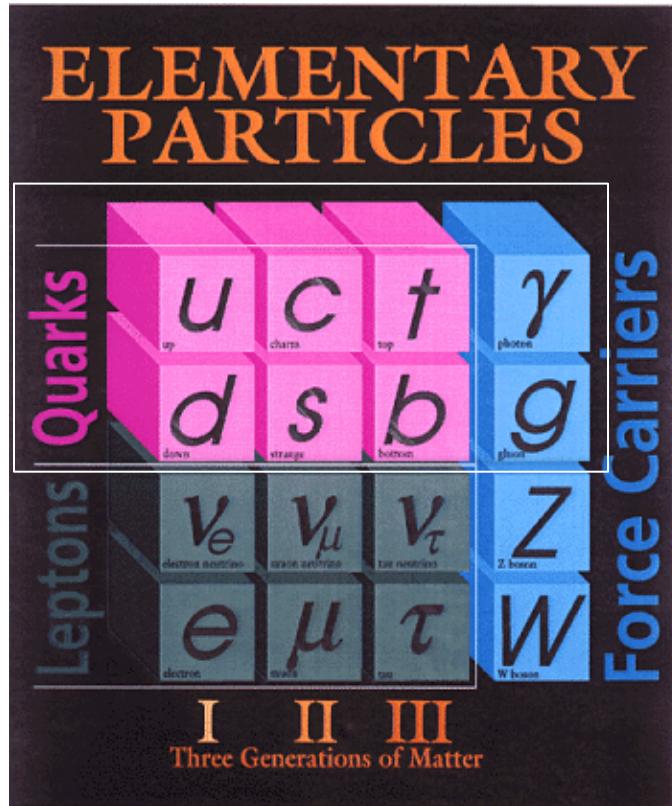
(1) Higgs Particle –

- Origin of Mass
- SM → The Theory

(2) QCD Phase Structure –

- Critical point, phase boundaries
- Confinement
- X_C symmetry
- Nucleon helicity structure
- ...
- Non-linear QCD at small-x
- ...
- ...
- Emerging properties

Quantum ChromoDynamics



- 1) QCD is the basic theory for strong interaction. Its degrees of freedom are well defined at short distance.
- 2) Little is known regarding the dynamical structures of matter, e.g. *the confinement, nucleon spin, the QCD phase structure...* Large α_s and strong coupling – QCD at long distance.

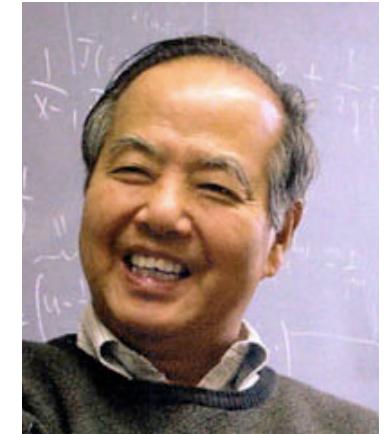
How to Address the Problem?

- The confinement:

Quarks are the basic building blocks of matter.

No free quarks are seen, confined within hadron:

$$\Delta v_0 \sim 1 \text{ fm}^3, \quad \rho_0 \sim 0.16 \text{ fm}^{-3}, \quad \varepsilon_0 \sim 0.15 \text{ GeV/fm}^3$$



- **Heavy ion collisions:** Large, hot/dense system

$$\Delta v \sim 1000 \text{ fm}^3 = 1000 v_0$$

T.D. Lee

$$\rho \gg 3 \text{ fm}^{-3} \sim 20 \rho_0$$

$$\varepsilon \gg 3 \text{ GeV/fm}^3 \sim 20 \varepsilon_0$$

Quark Gluon Plasma (QGP)

↗ **QGP: Quarks and gluons are ‘freely’ moving in a large volume**

New form of **matter with partonic degrees of freedom**

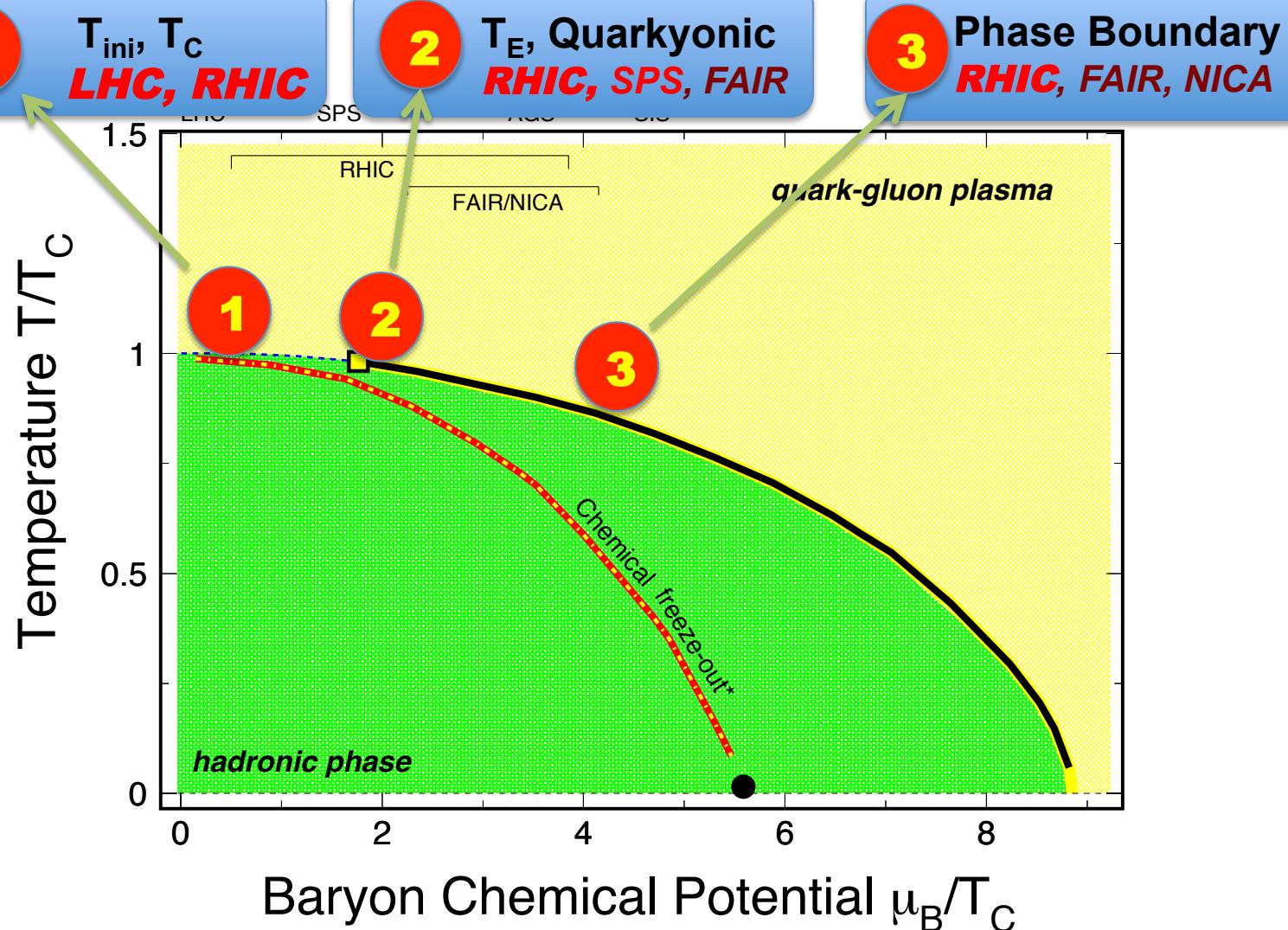
↗ **QCD Phase Structure**

- Connection with other fields

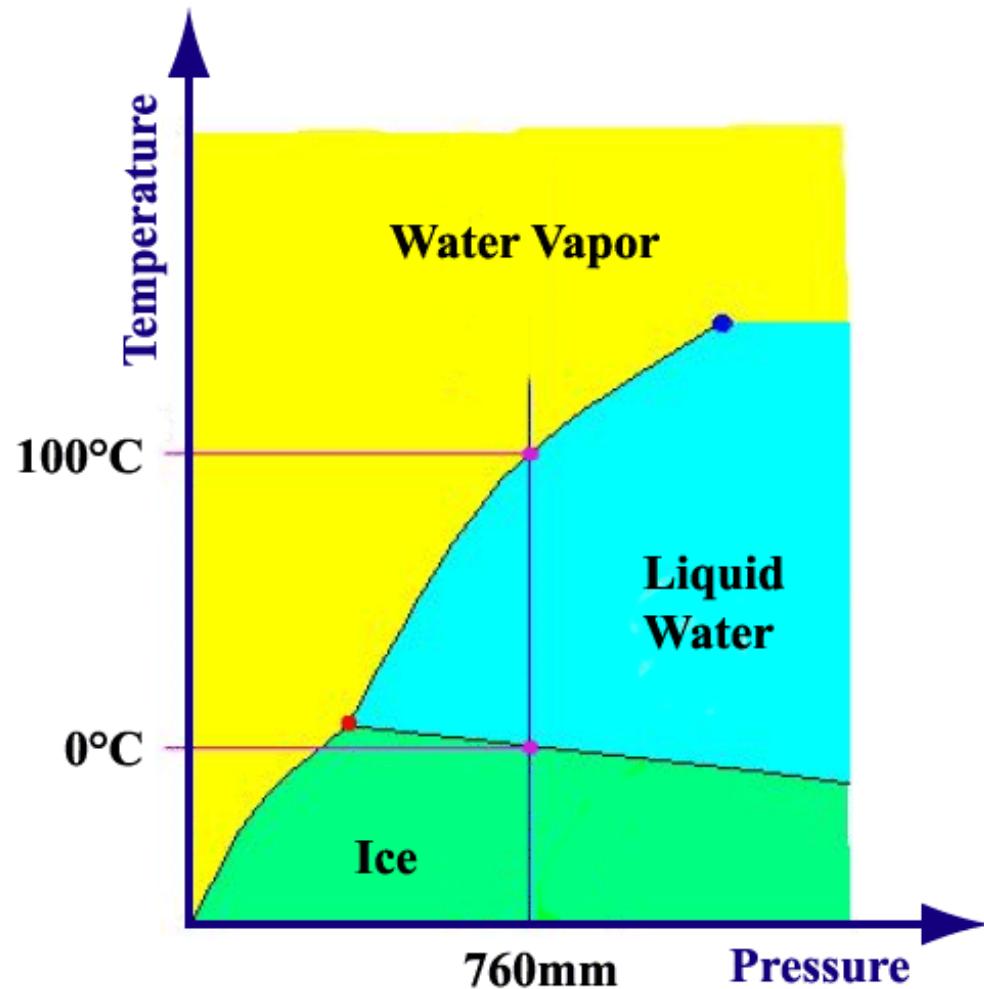
cosmology, origin of the universe, evolution of the universe

quantum statistics with partons

The QCD Phase Diagram and High-Energy Nuclear Collisions



Phase Diagram: Water



Phase diagram: A map shows that, at given degrees of freedom, how matter organize itself under external conditions.

Water: H_2O

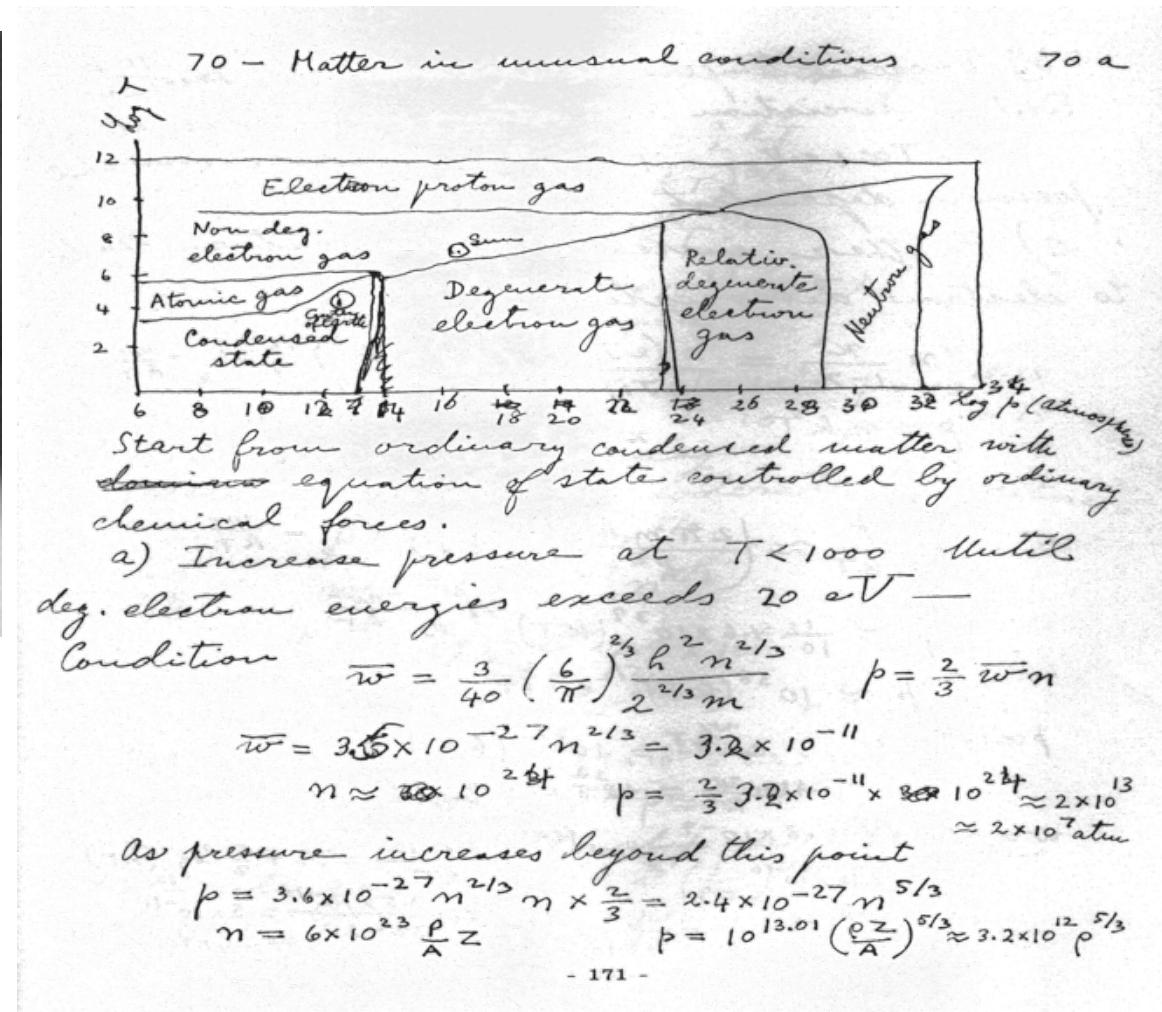
The QCD phase diagram: structure of matter with quark- and gluon-degrees (color degrees) of freedom.

QCD Phase Diagram (1953)



E. Fermi

E. Fermi: "Notes on Thermodynamics and Statistics" (1953)





Outline

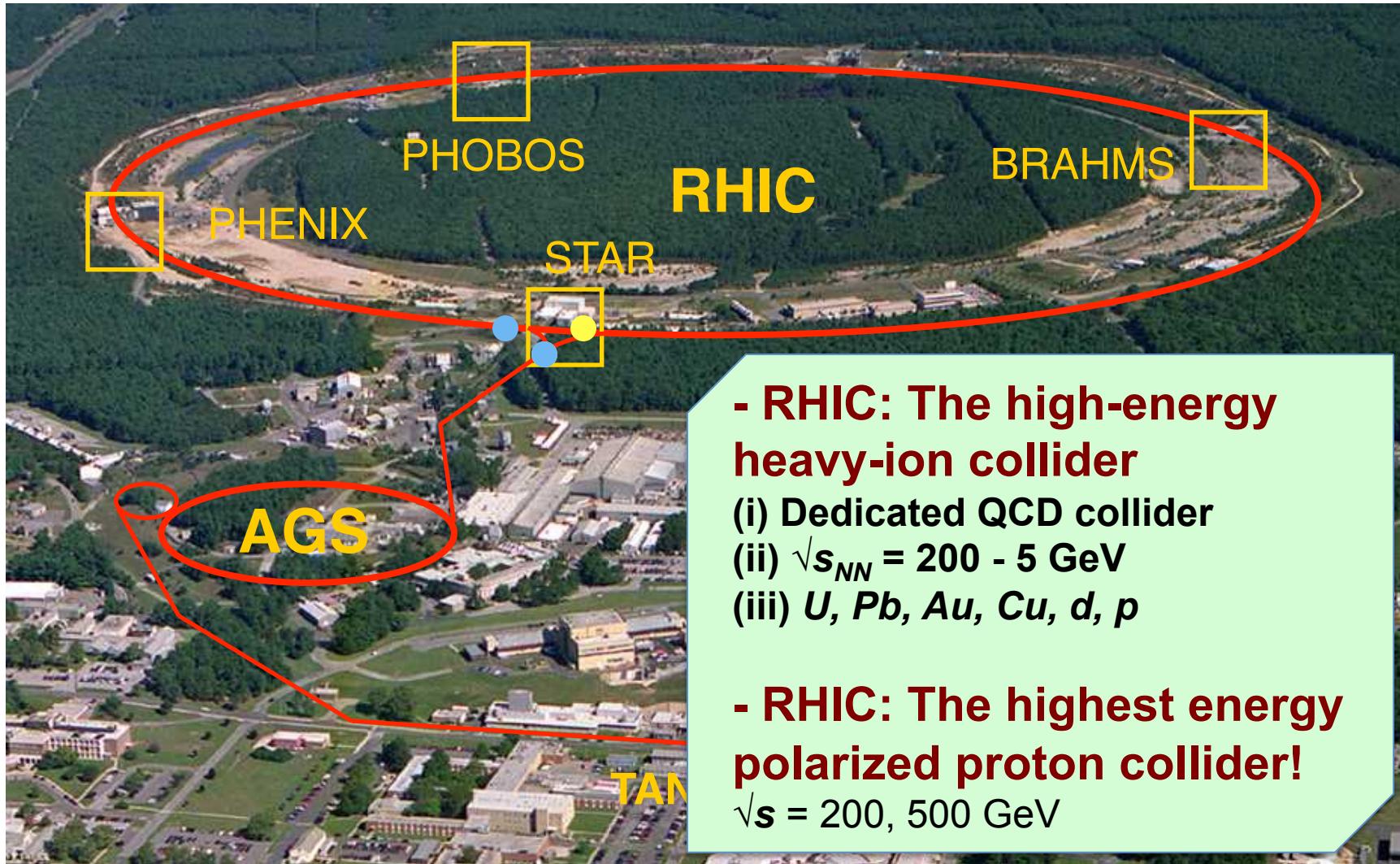


- 1) Introduction: *QCD phase structure*
- 2) Experiments at RHIC and LHC
- 3) Selected Results: *QCD matter formation*
- 4) Summary and Outlook



Relativistic Heavy Ion Collider

Brookhaven National Laboratory (BNL), Upton, NY

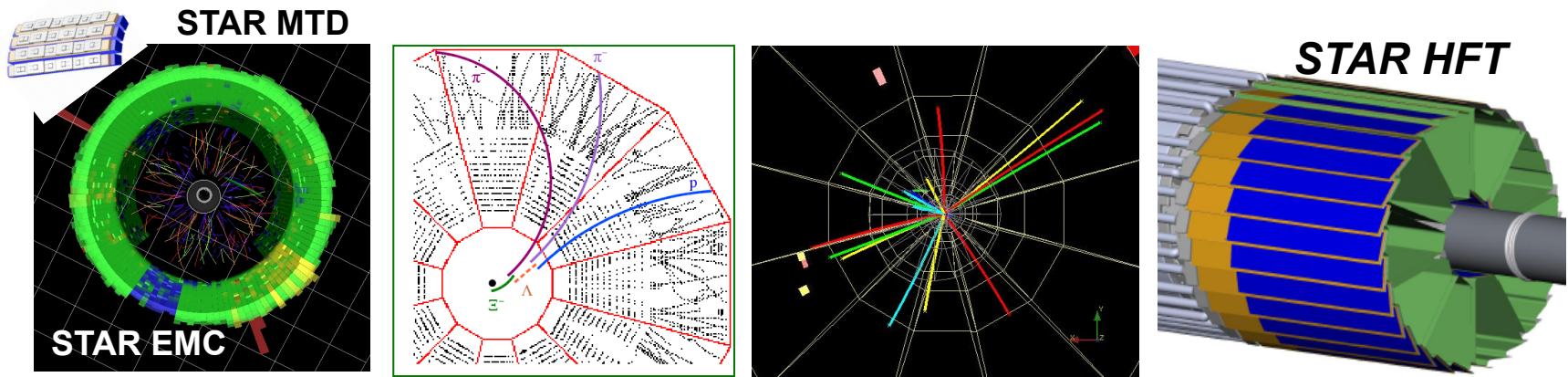
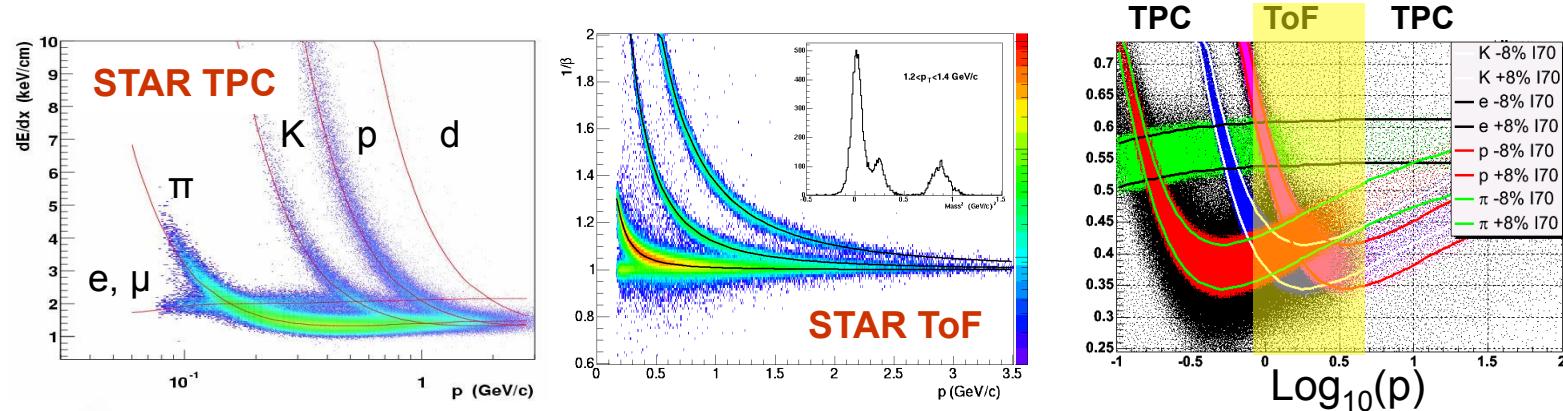


Animation M. Lisa

STAR Collaboration



Particle Identification at STAR



Neutral particles

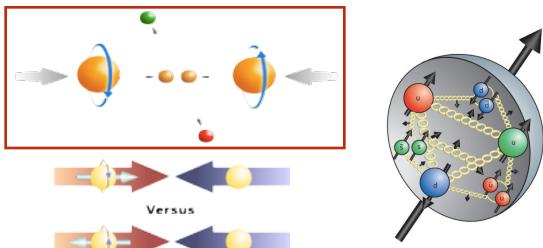
Strange hyperons

Jets

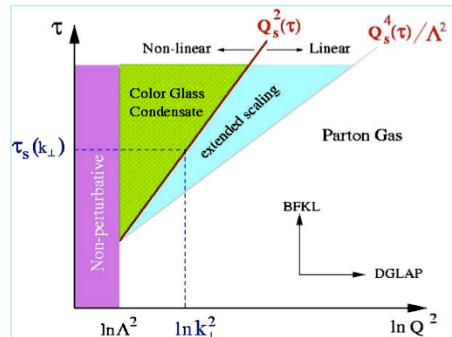
Heavy Quark Hadrons

Multiple-fold correlations for both HI and Spin physics!

STAR Physics Focus



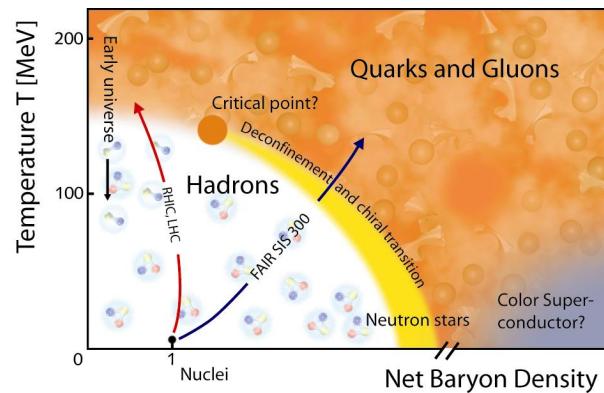
Polarized $p+p$ program
 - Study *proton intrinsic properties*



Forward program

- Study low-x properties, initial condition, search for **CGC**
- Study elastic and inelastic processes in pp2pp

2020 -
eRHIC
 (eSTAR)



1) At 200 GeV at RHIC

- Study *medium properties, EoS*
- pQCD in hot and dense medium

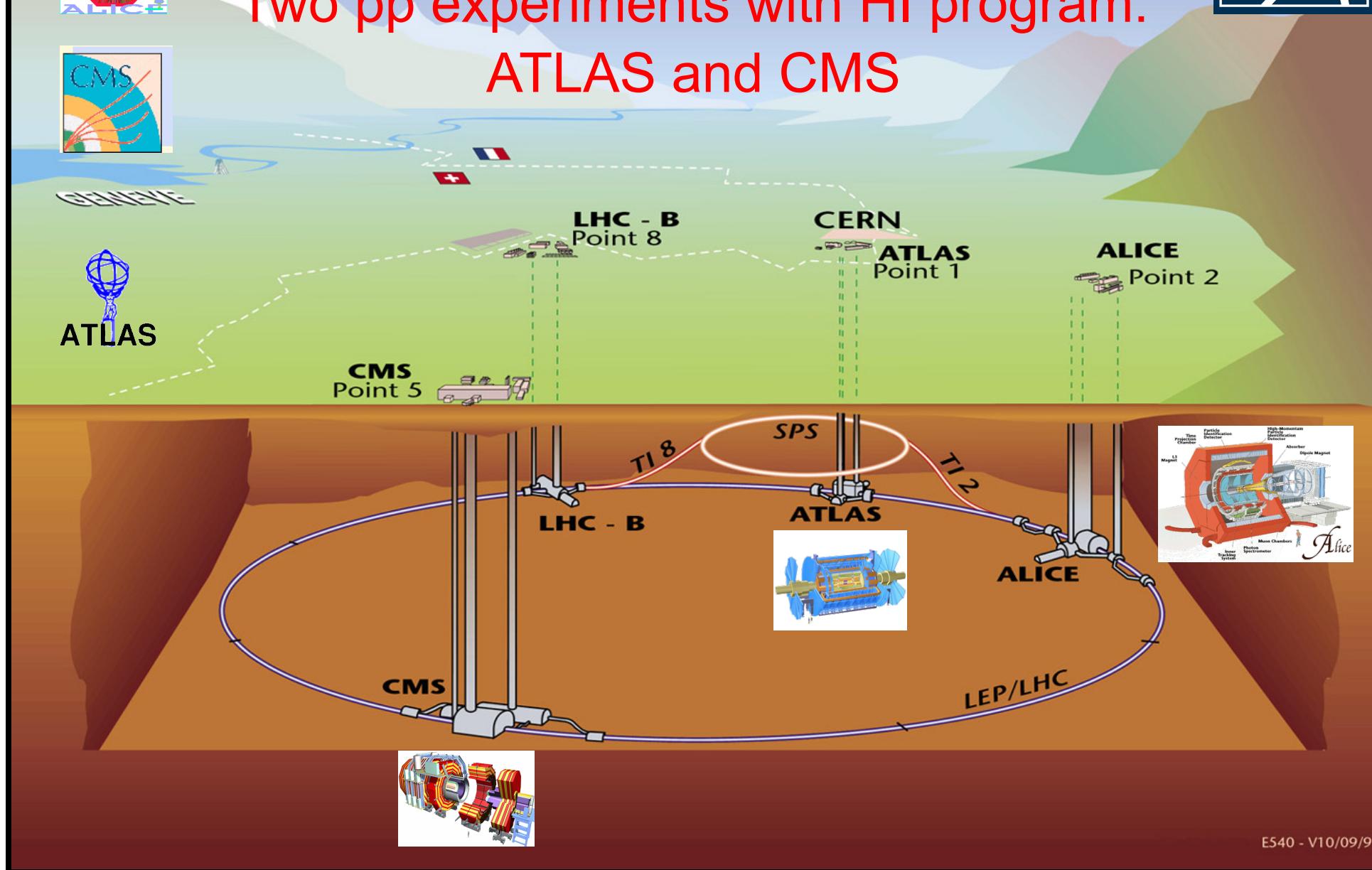
2) RHIC beam energy scan (BES)

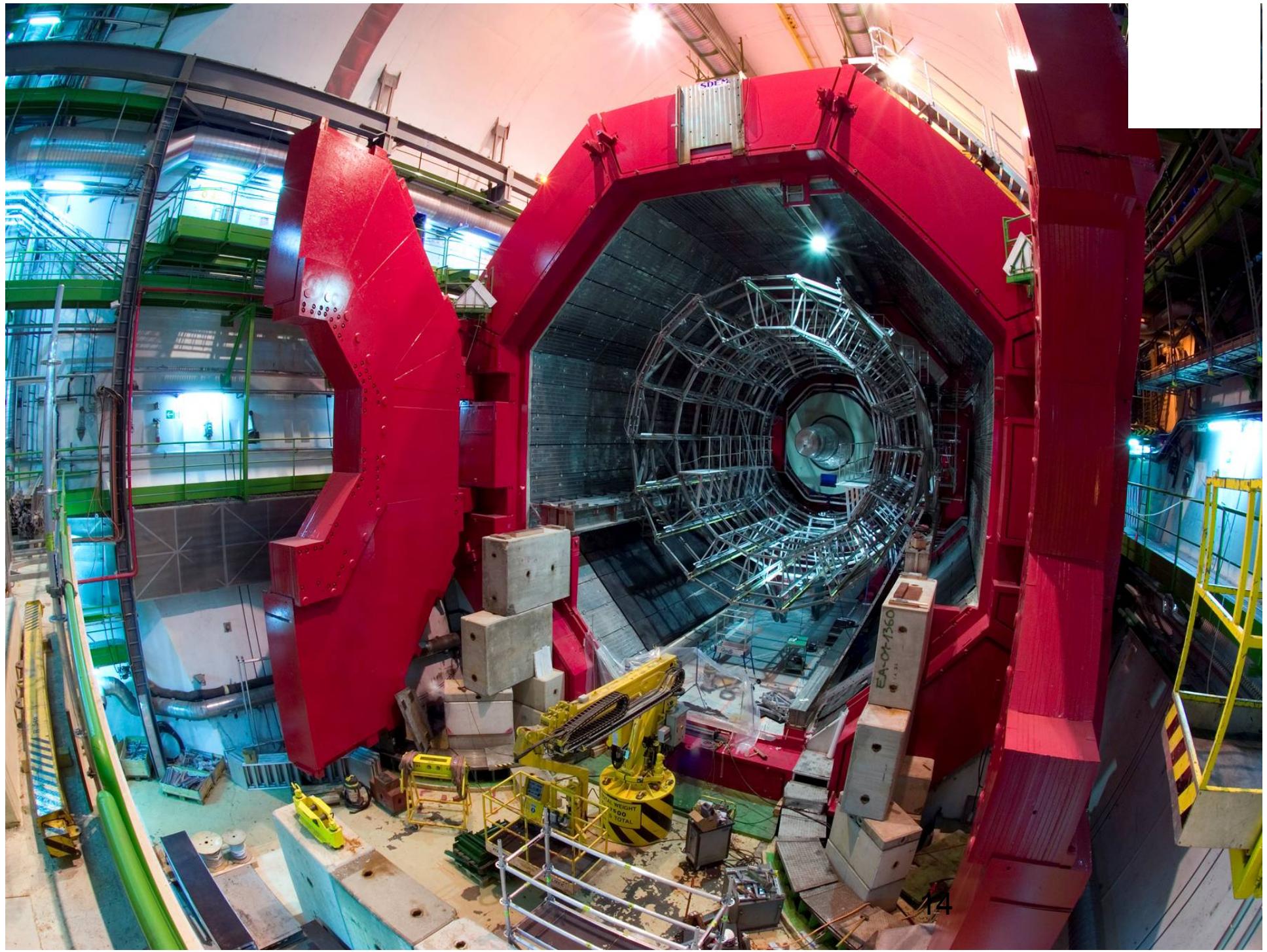
- Search for the *QCD critical point*
- Chiral symmetry restoration

Overall view of the LHC experiments.

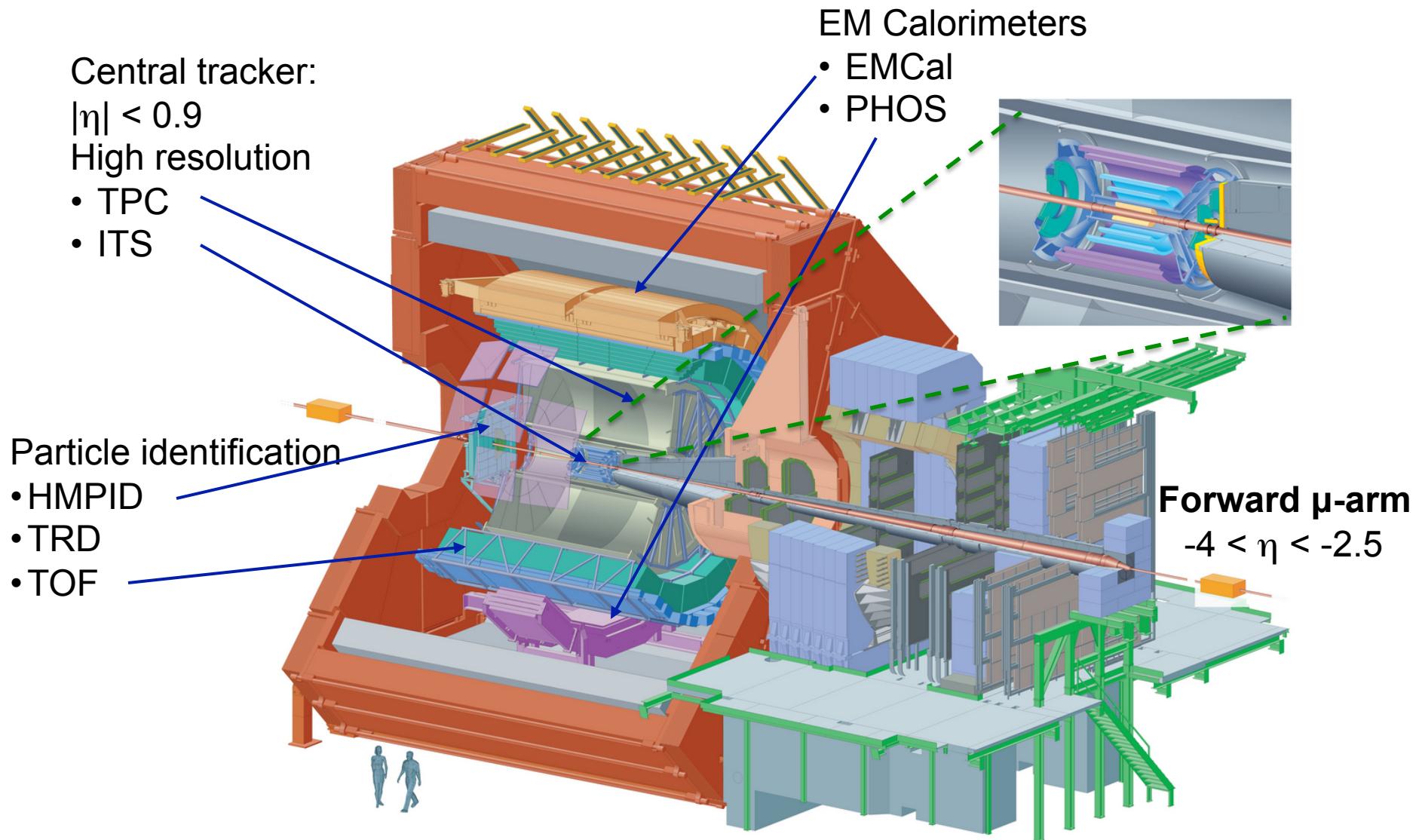


One dedicated HI experiment: ALICE
Two pp experiments with HI program:
ATLAS and CMS

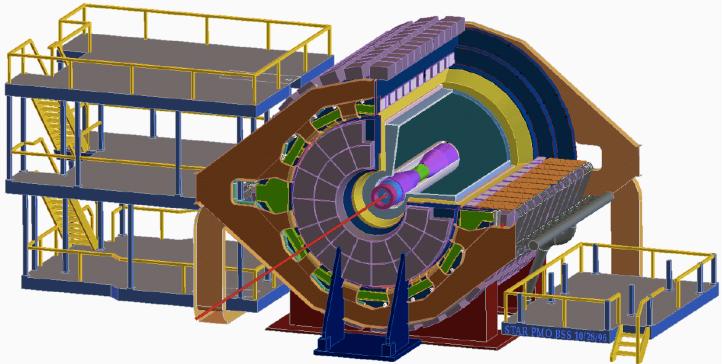




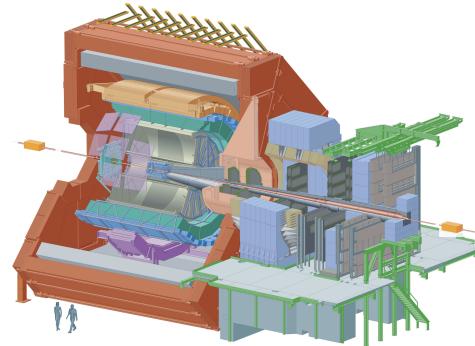
ALICE Experiment



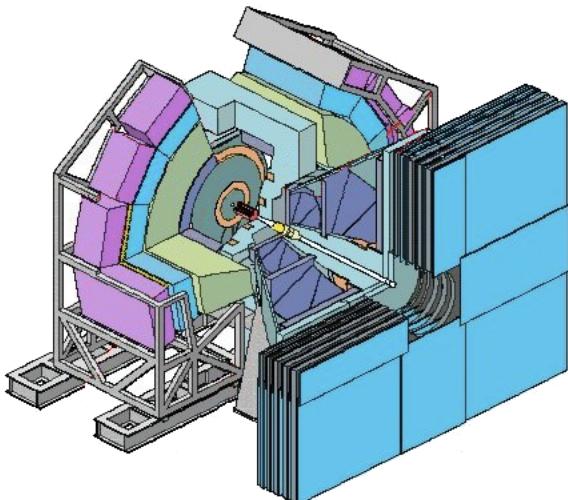
High-Energy Nuclear Collider Experiments



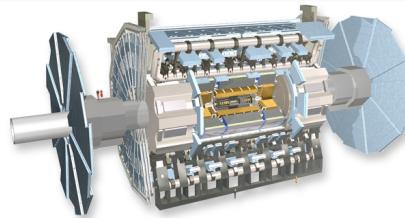
STAR (Solenoidal Tracker At RHIC)



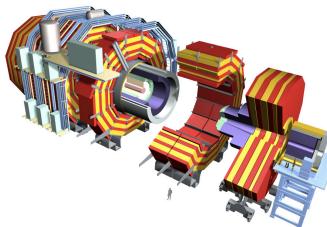
ALICE (A Large Ion Collider Experiment)



PHENIX (Pioneering High Energy Nuclear Ion Experiment)



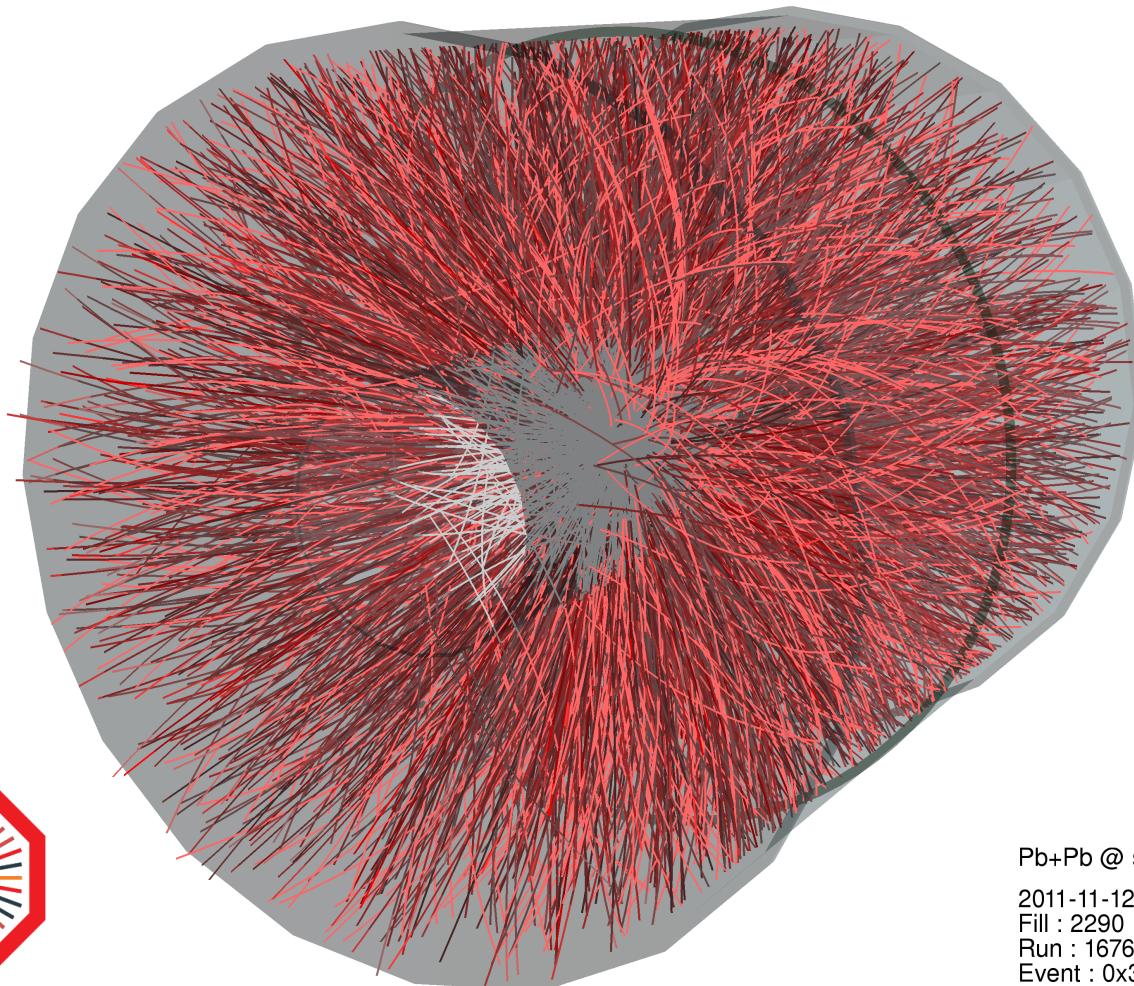
ATLAS (A Toroidal LHC Apparatus)



CMS (Compact Muon Solenoid)



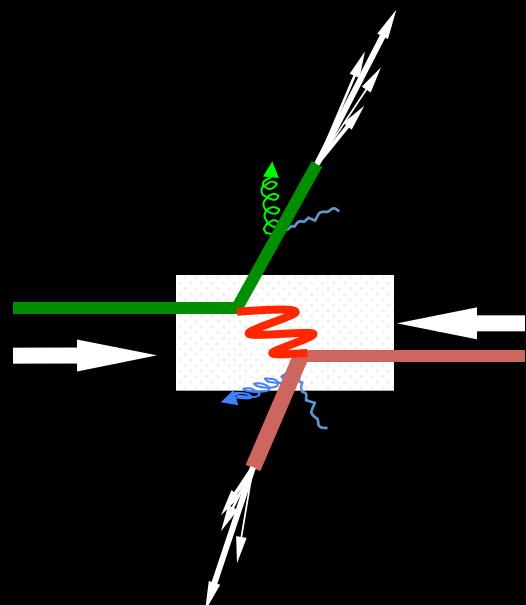
Pb-Pb Event Display



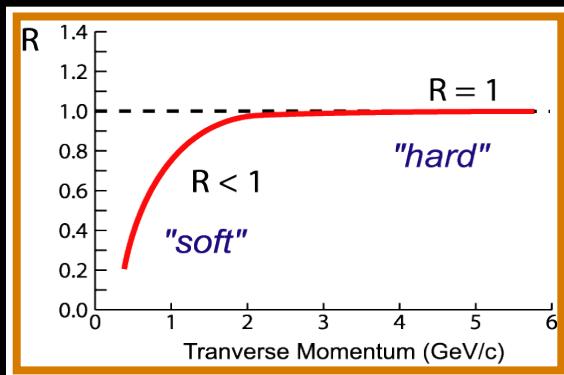
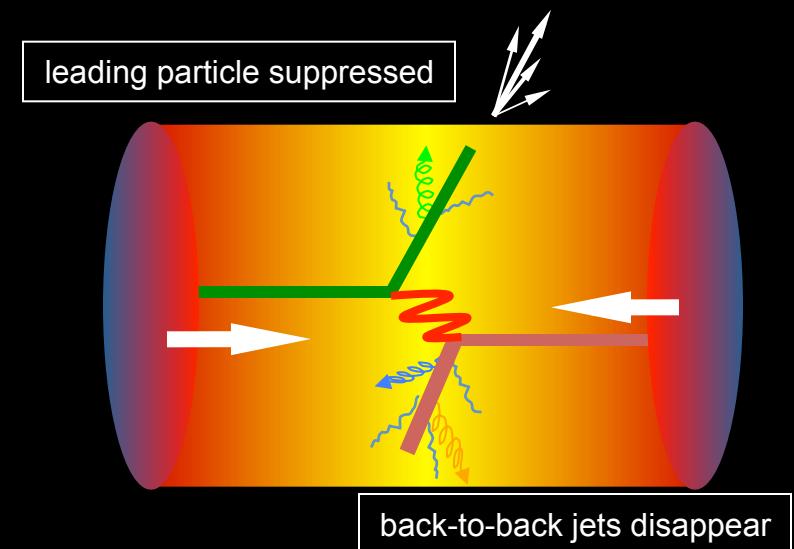
Pb+Pb @ $\sqrt{s} = 2.76$ ATeV
2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

Jet Quenching at RHIC

$p + p$



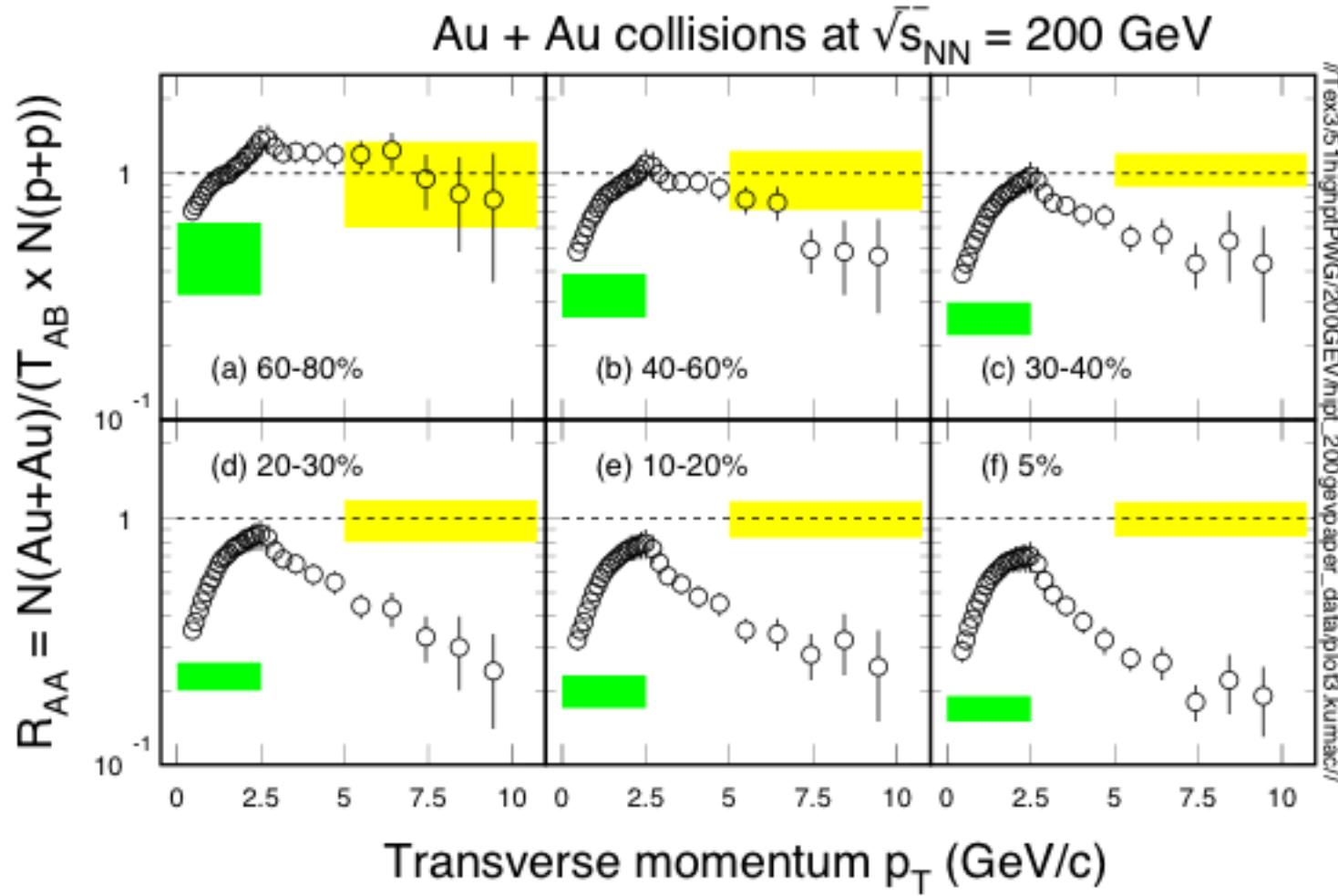
$Au + Au$



Nuclear Modification Factor:

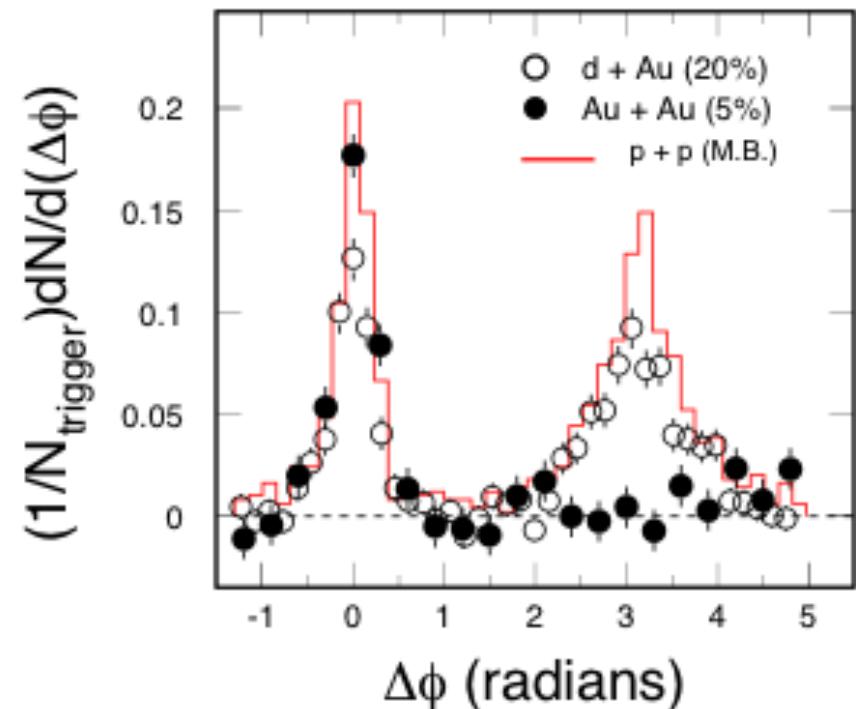
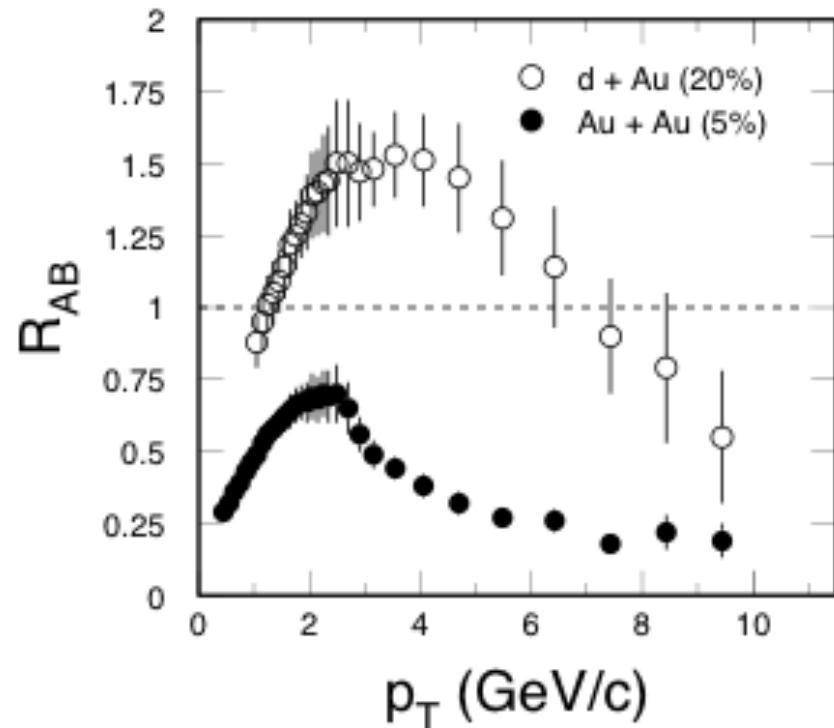
$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2\sigma^{AA}/dp_T dy}{d^2\sigma^{NN}/dp_T dy}$$

Hadron Suppression at RHIC



Hadron suppression in more central Au+Au collisions!

Suppression and Correlation



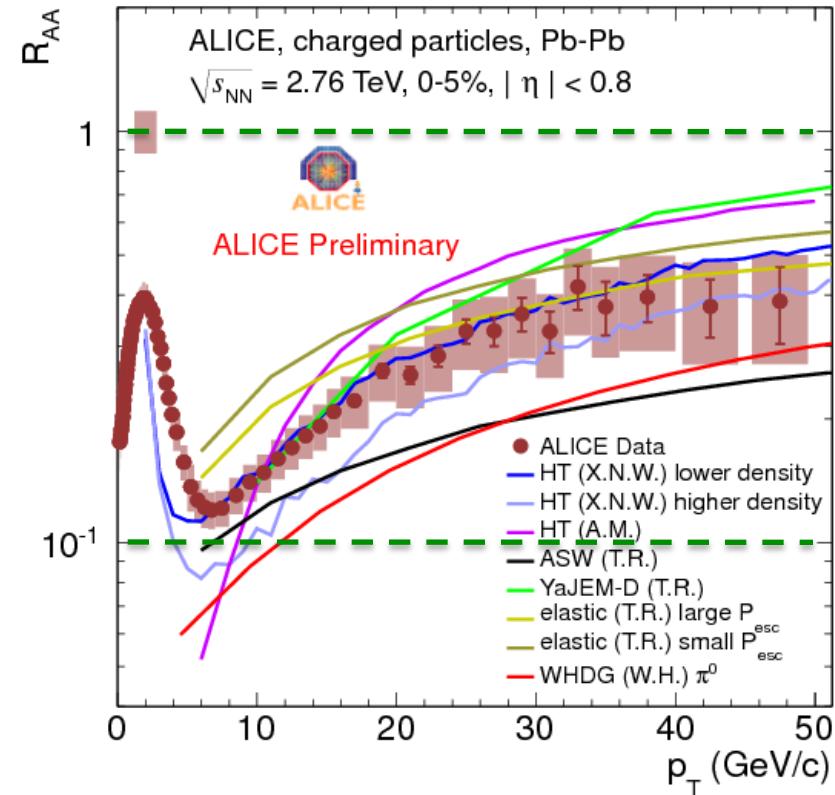
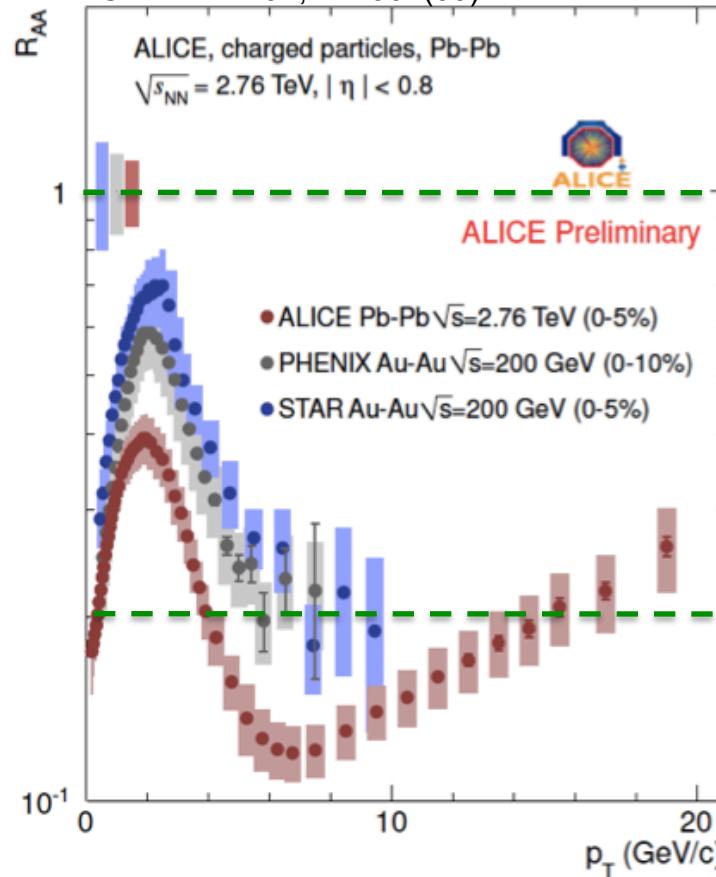
In central $\text{Au} + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV: light quark hadrons and away-side jets are suppressed.

Energy density at RHIC: $\varepsilon > 5 \text{ GeV/fm}^3 \sim 30^* \varepsilon_0$

pQCD predictions: *M. Gyulassy & X.N. Wang, 1992*

Nuclear Modification Factor

PHENIX: PRC69, 034910(04)
STAR: PRL91, 172302(03)



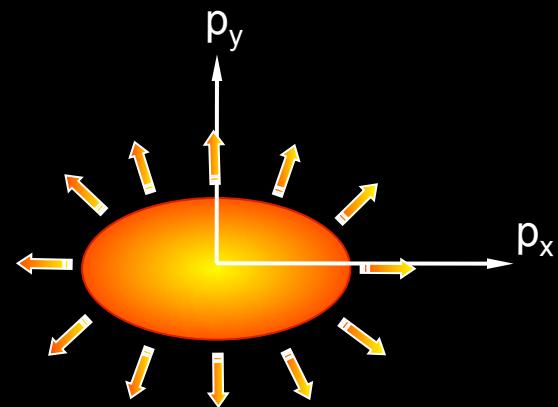
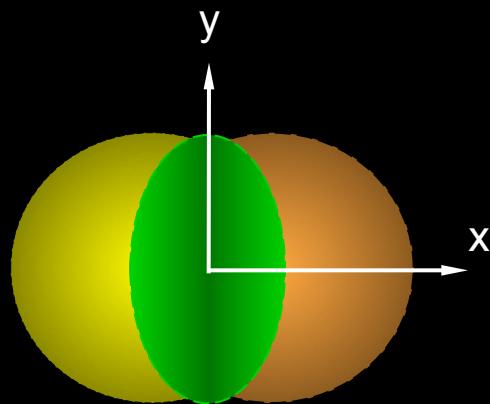
王新年

- 1) At LHC(2.76TeV), the energy loss is stronger than that from RHIC (0.2TeV)
 → hotter/denser medium created at higher collision energy
- 2) pQCD predictions consistent at larger p_T region: $> 10 \text{ GeV}/c$

Anisotropy Parameter v_2

coordinate-space-anisotropy

↔ momentum-space-anisotropy



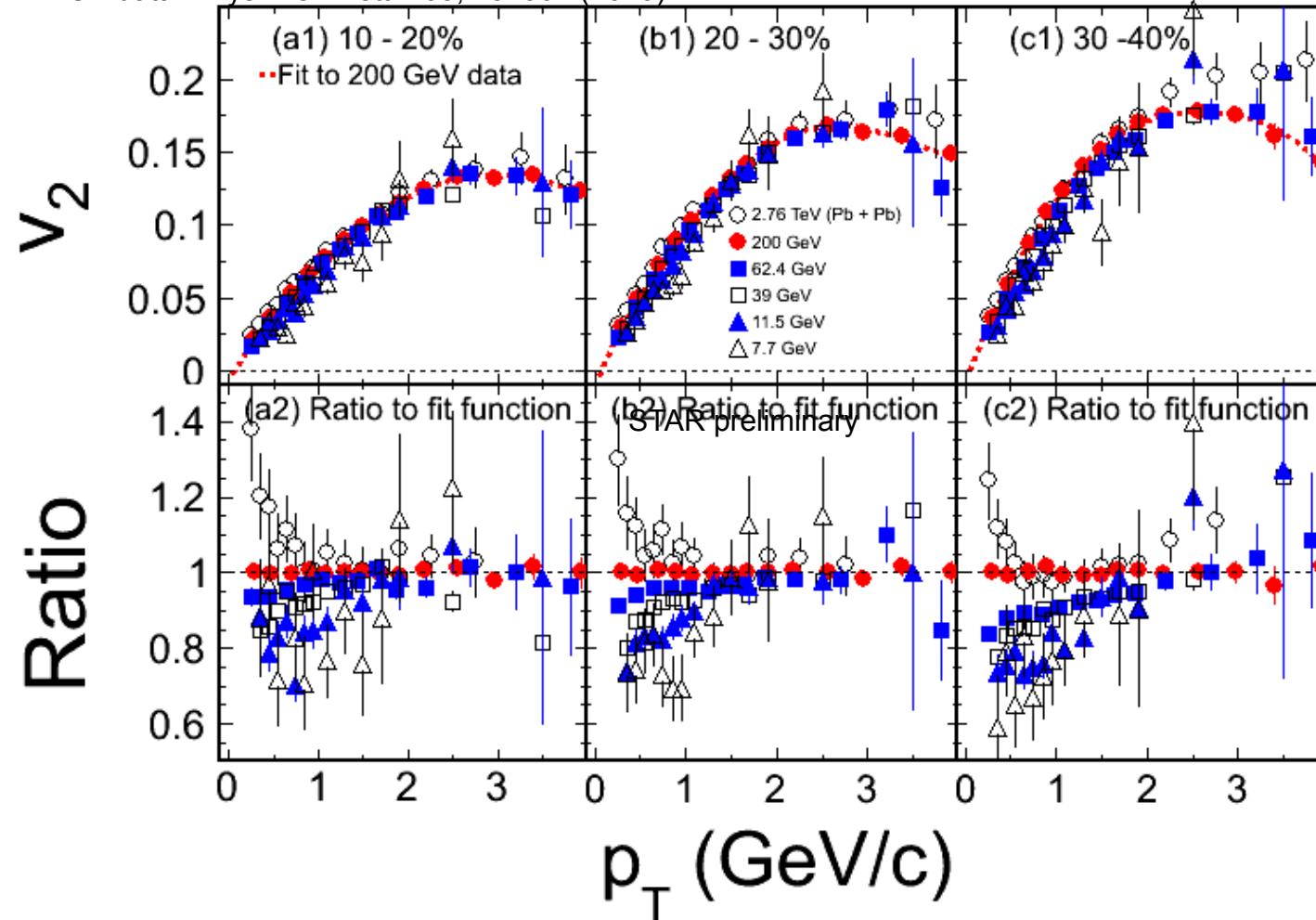
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1} \left(\frac{p_y}{p_x} \right)$$

Initial/final conditions, EoS, degrees of freedom

Energy Dependence

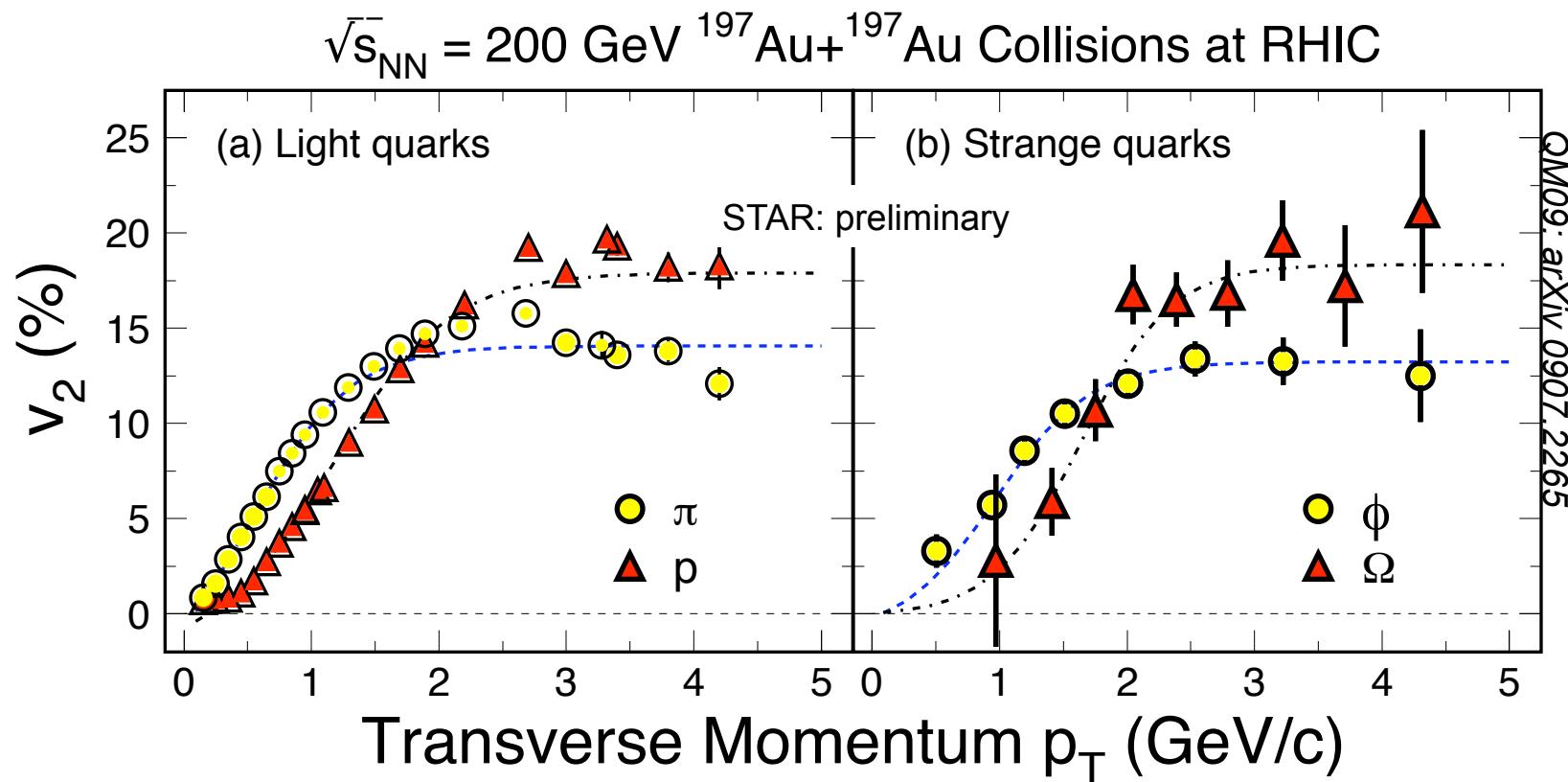
ALICE data: Phys. Rev. Lett. 105, 252302 (2010)



Stronger collective flow at higher collision energies

施梳苏, STAR, CPOD2011

Partonic Collectivity at RHIC



Low p_T ($\leq 2 \text{ GeV}/c$): hydrodynamic mass ordering

High p_T ($> 2 \text{ GeV}/c$): **number of quarks scaling**

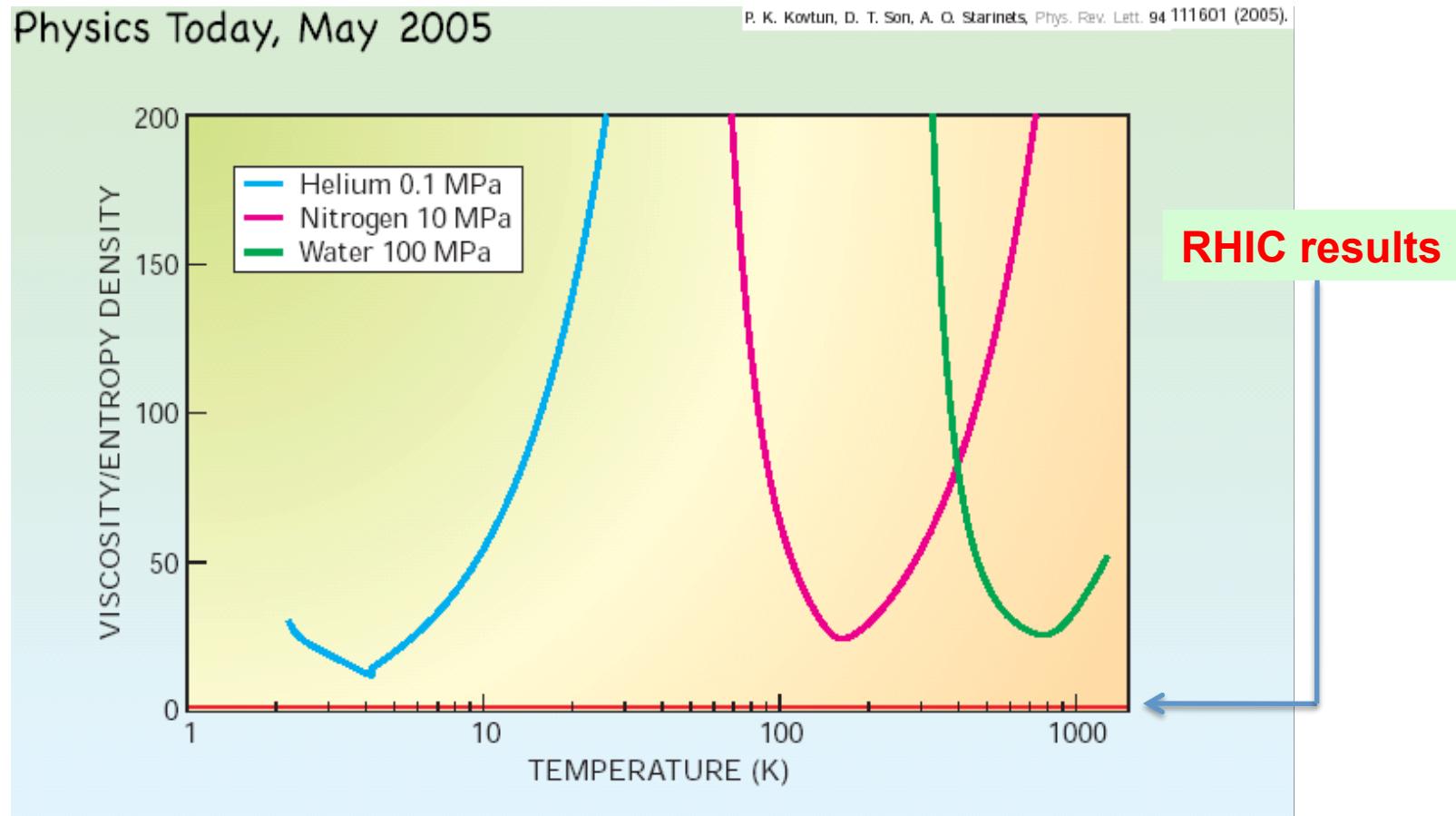
→ **Partonic Collectivity, necessary for QGP!**

→ **De-confinement in Au+Au collisions at RHIC!**

Low η/s for QCD Matter at RHIC

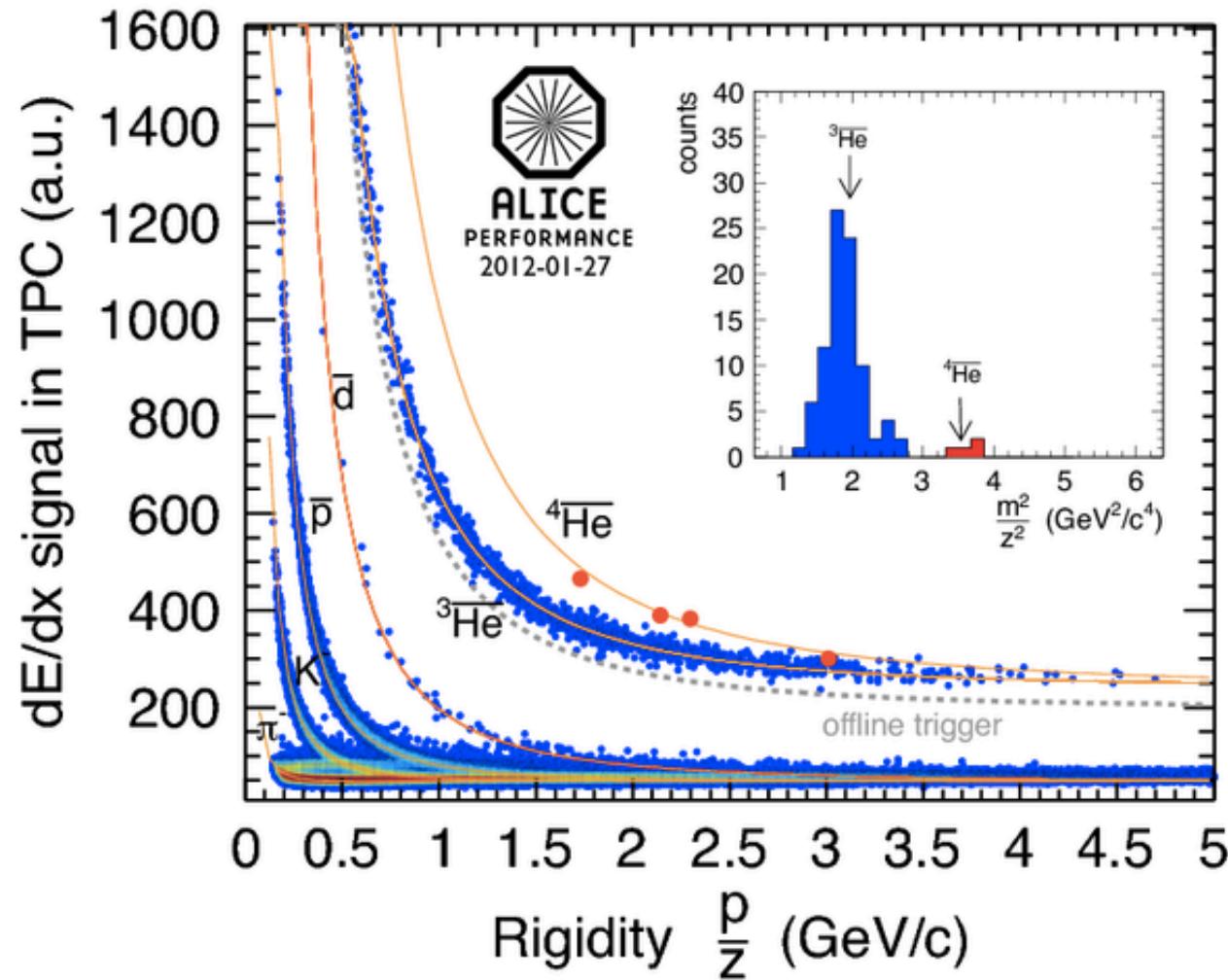
Physics Today, May 2005

P. K. Kovtun, D. T. Son, A. O. Starinets, Phys. Rev. Lett. 94 111601 (2005).



- 1) $\eta/s \geq 1/4\pi$
- 2) $\eta/s(\text{QCD matter}) < \eta/s(\text{QED matter})$

Antimatter at LHC



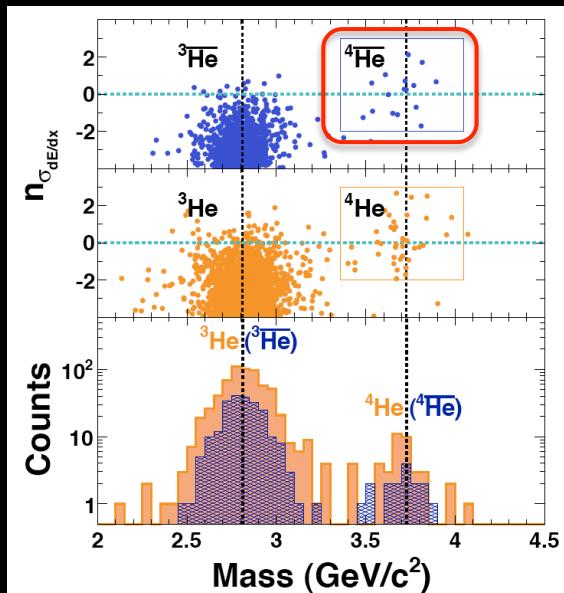
nature

April, 2011

“Observation of the Antimatter Helium-4 Nucleus”

by STAR Collaboration

***Nature*, 473, 353(2011).**

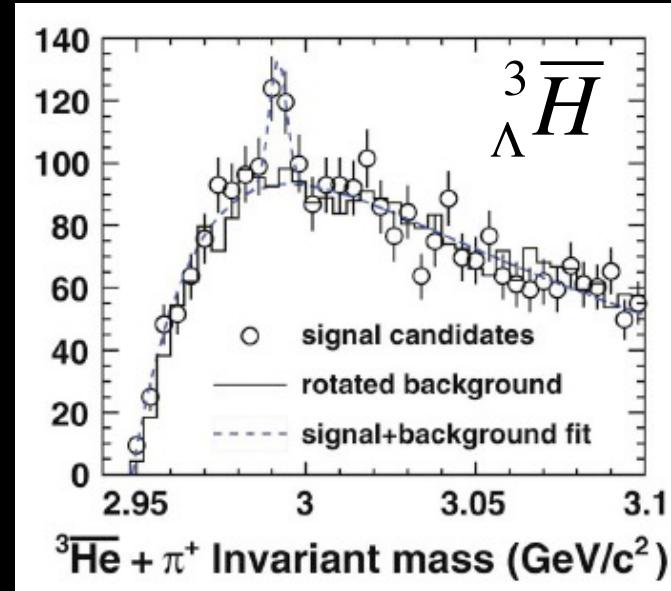
**Science**

March, 2010

“Observation of an Antimatter Hypernucleus”

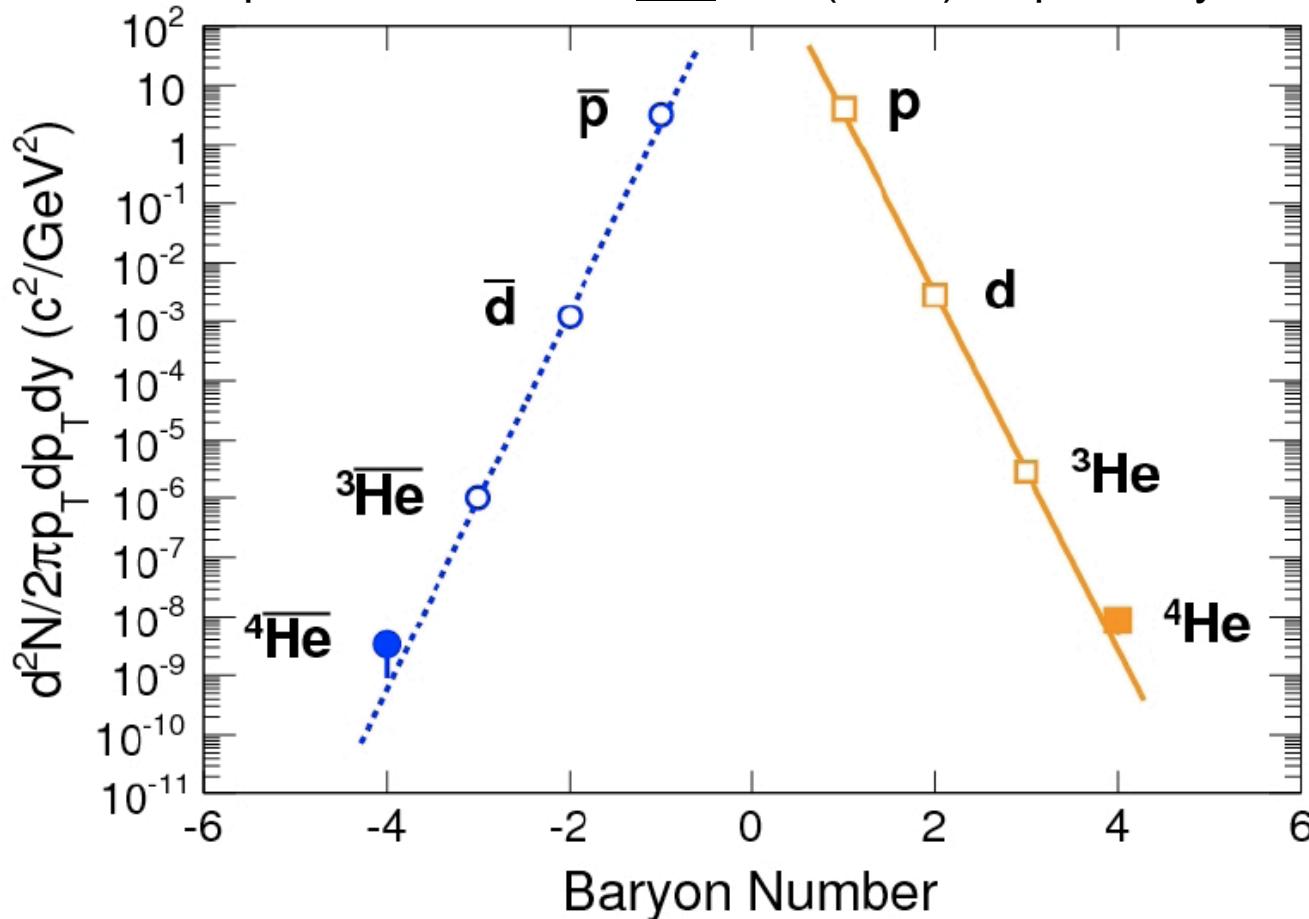
by STAR Collaboration

***Science*, 328, 58(2010).**



Light Nuclei Productions at RHIC

STAR Experiment: *Nature*, 473, 353(2011), Top 100 by *Discover Magazine*



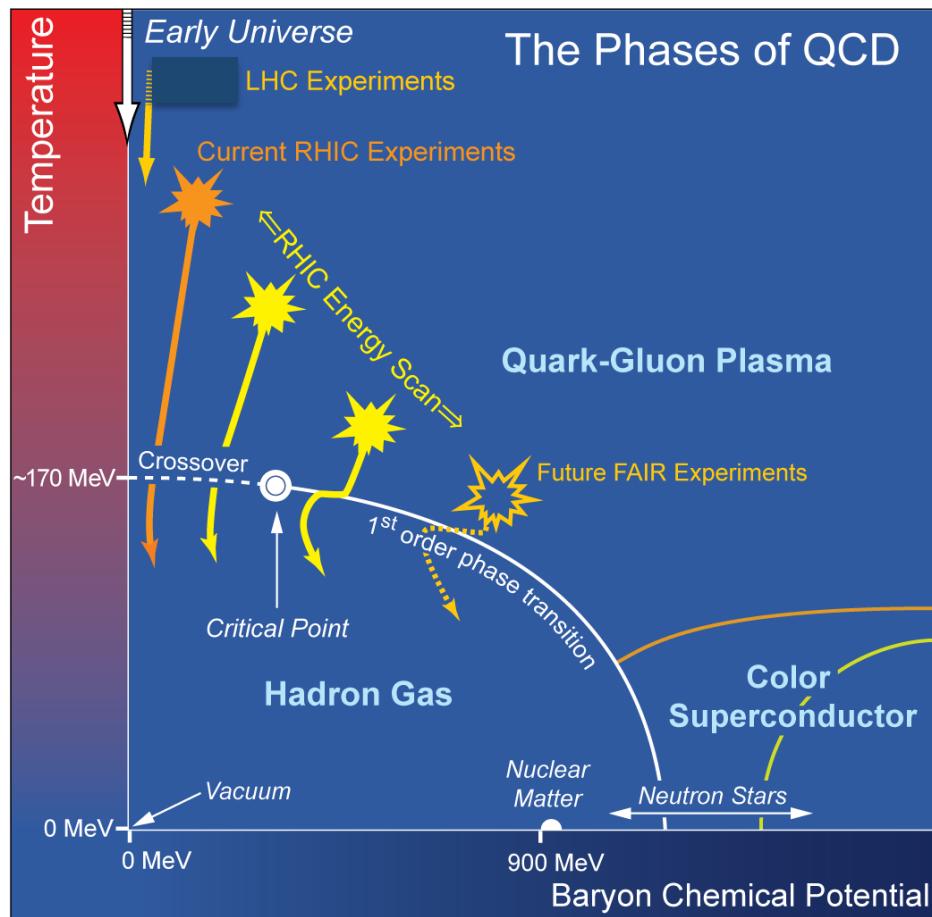
清华大学
中国科技大学
华中师范大学
中国科学院
上海应用核物理所
近代物理所

- 1) In high-energy nuclear collisions, $N(d) \gg N(\alpha)$:
QGP → (anti)light nuclei via coalescence
- 2) In the Universe, $N(d) \ll N(\alpha)$: $N(\text{anti-}\alpha)$?

Beam Energy Scan at RHIC

Study QCD Phase Structure

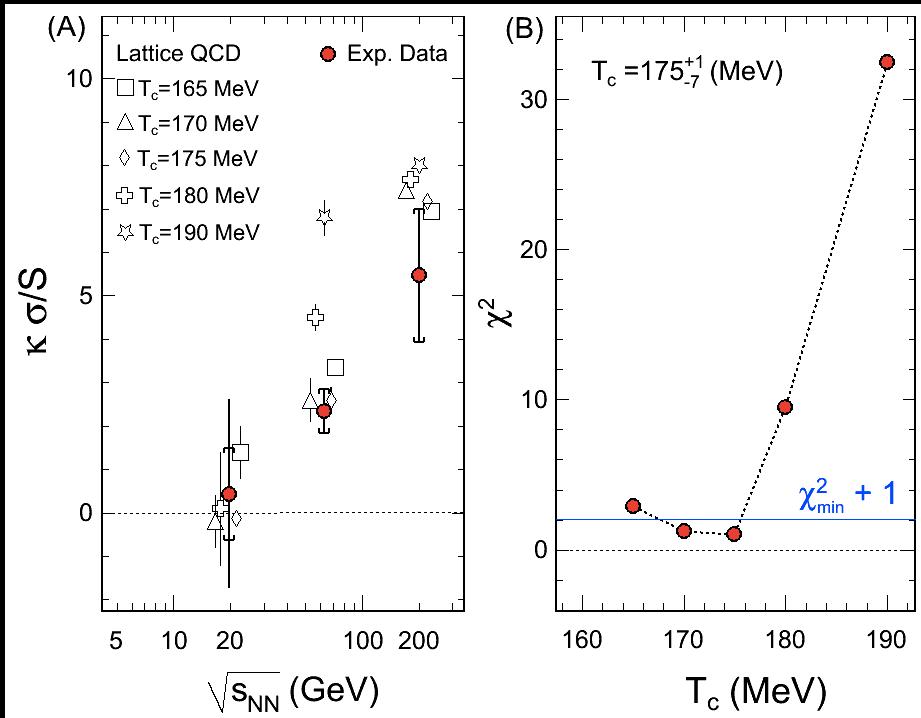
- Signals of phase boundary
- Signals for critical point



Observations:

- (1) Azimuthally HBT**
1st order phase transition
- (2) Directed flow v_1**
1st order phase transition
- (3) Dynamical correlations**
partonic vs. hadronic dof
- (4) v_2 - NCQ scaling**
partonic vs. hadronic dof
- (5) Fluctuations**
Critical point, correl. length

- <http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493>
 - arXiv:1007.2613



Science June, 2011
 AAAS

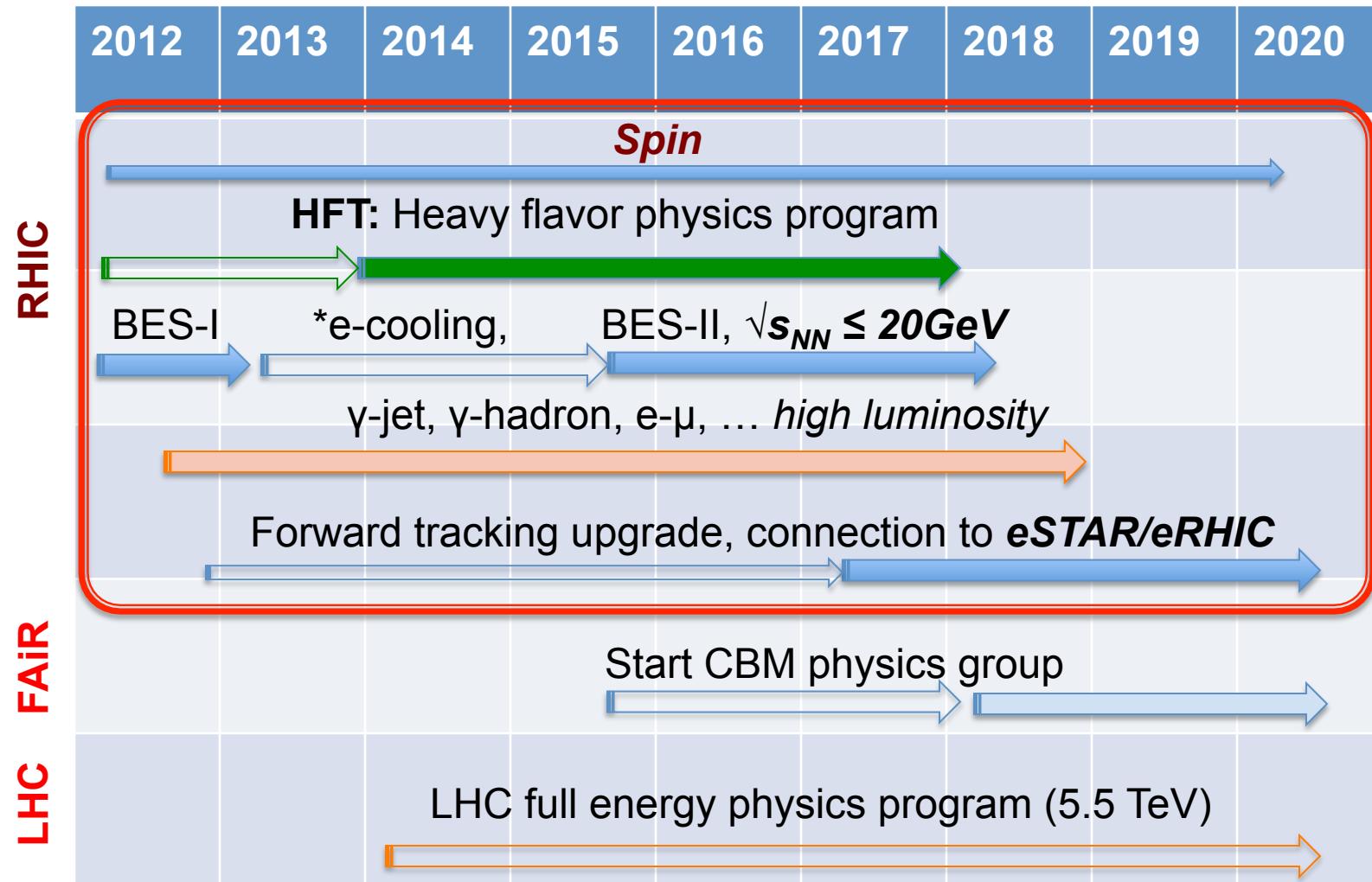
“Scale for the Phase Diagram of Quantum Chromodynamics”

Science, 332, 1525(2011)

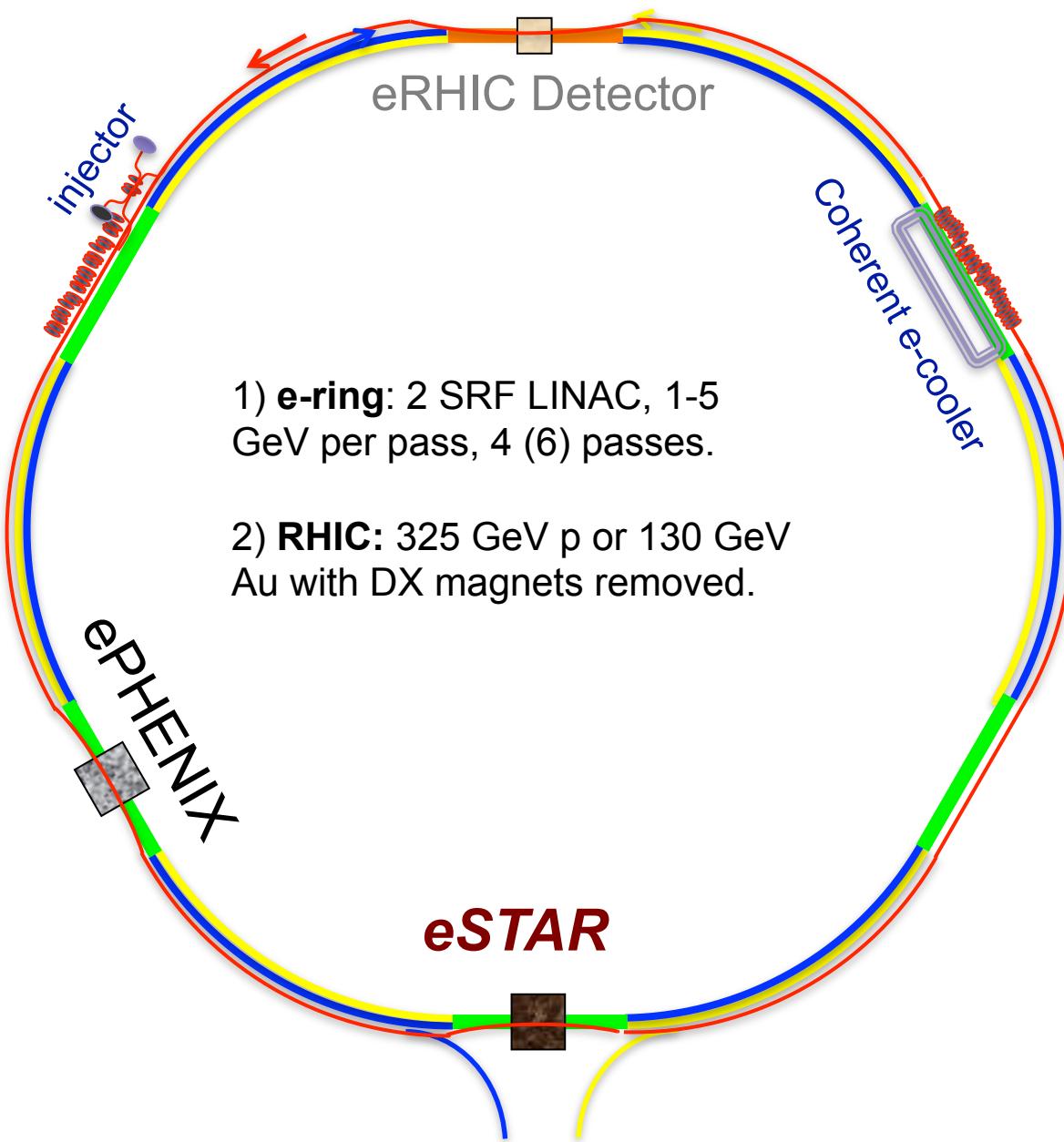
- 1) Central collisions at RHIC, the high moments measurements are consistent with thermal equilibrium assumption
- 2) Scale of LGT, determined with the data, is: $T_c = 175^{+1}_{-7}$ (MeV)

STAR, *PRL* 105, 22303(2010); S. Gupta, 罗晓峰, B. Mohanty, H.G. Ritter, 许怒, *Science*, 332, 1525(2011); F. Karsch and K. Redlich, *PLB* 695, 136(2011); R.V. Gavai and S. Gupta, *PLB* 696, 459(2011).

Study QCD Phase Structure



Outlook: eRHIC



eRHIC:
(2022-2025)

e beam: 20-30 GeV
p beam: 325 GeV
ion beam: 130 GeV
1 dedicated detector

ePHENIX/eSTAR:
(2018-2022)

e beam: 5 GeV
p beam: 325 GeV
ion beam: 130 GeV

S. Vigdor: 2010 RHIC operational review

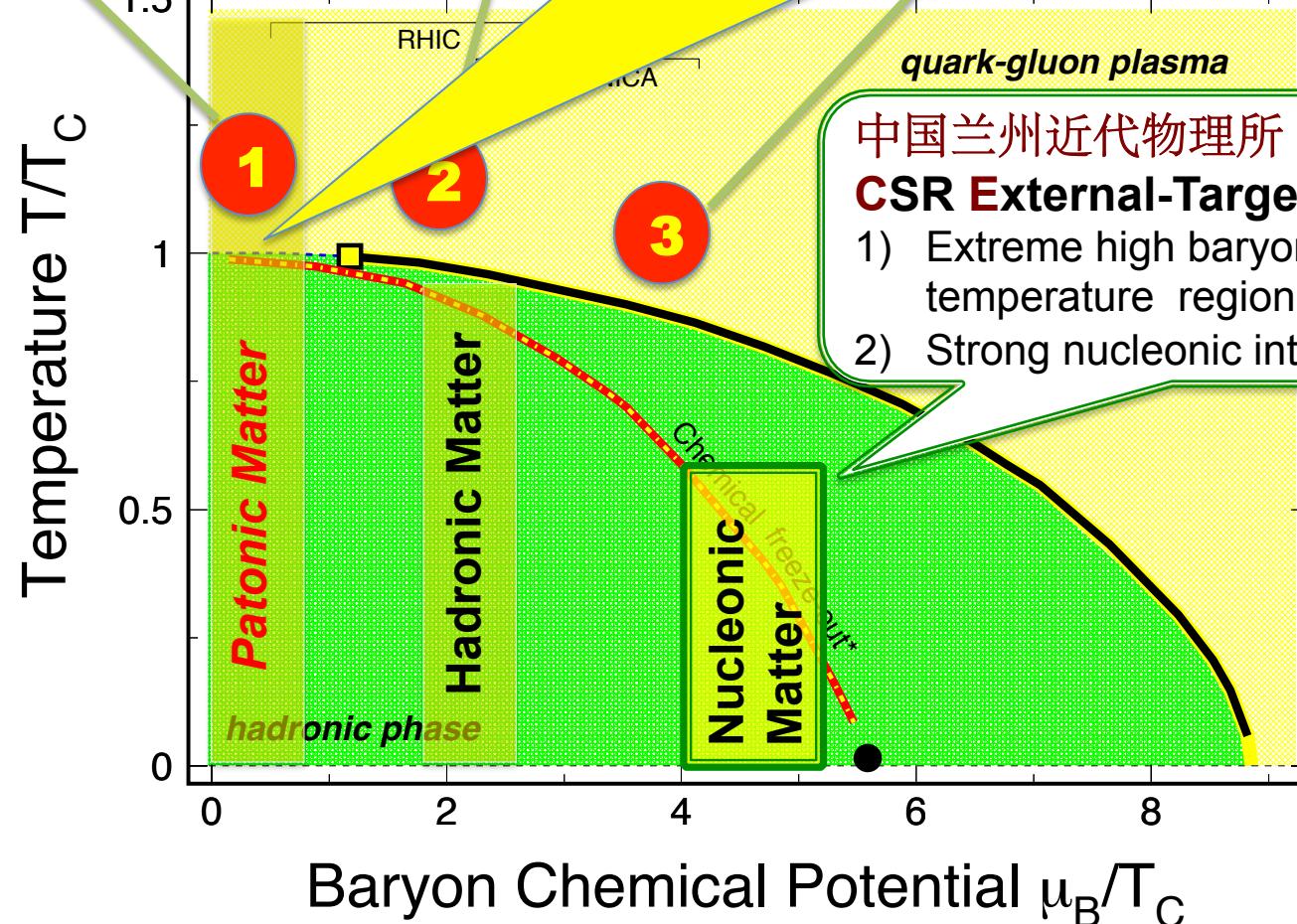
Outlook:

QGP Properties at RHIC and LHC (0.2 - 5.5 TeV AA and pA Collisions)

1

T_{ini}, T_c
LHC, RHIC

- Upgrade for HF hadron measurements
- di-leptons: v_2 , p_T spectra, R_{AA} , ... vs. mass





Summary and Outlook



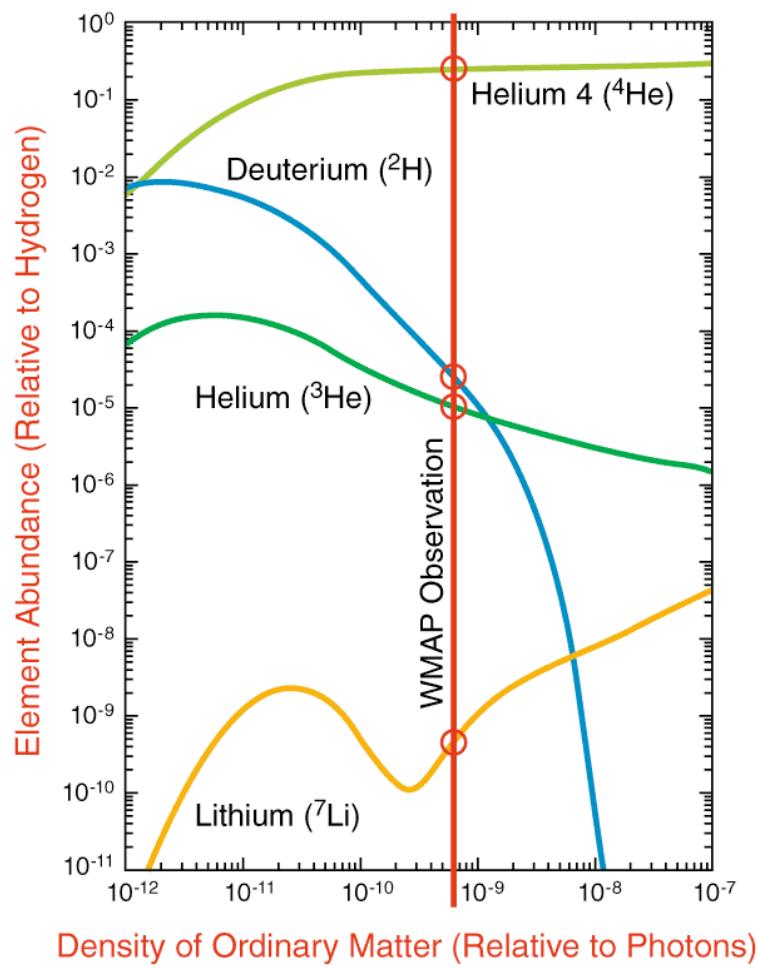
- 1) ALICESTAR at RHIC: Dedicated facility for studying matter with QCD degrees of freedom:
 - *Properties of QGP*
 - *Sea quark and gluon contributions to proton helicity structure*
 - *QCD critical point, phase boundary*
- 2) Future: EIC (eRHIC, 2022 - ...)
 - *Partonic structures of nucleon and nuclei*
 - *Understanding the dynamical evolution from cold nuclear matter to hot QGP*

Phase Structures of QCD Matter

*Many Thanks to the
Organizers!*

Nu Xu

Atomic Nuclei Formation



NASA/WMAP Science Team
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

$$\frac{n_B}{n_\gamma} \approx 10^{-9}$$

